

# ST7-DRS

## SPACE TECHNOLOGY 7

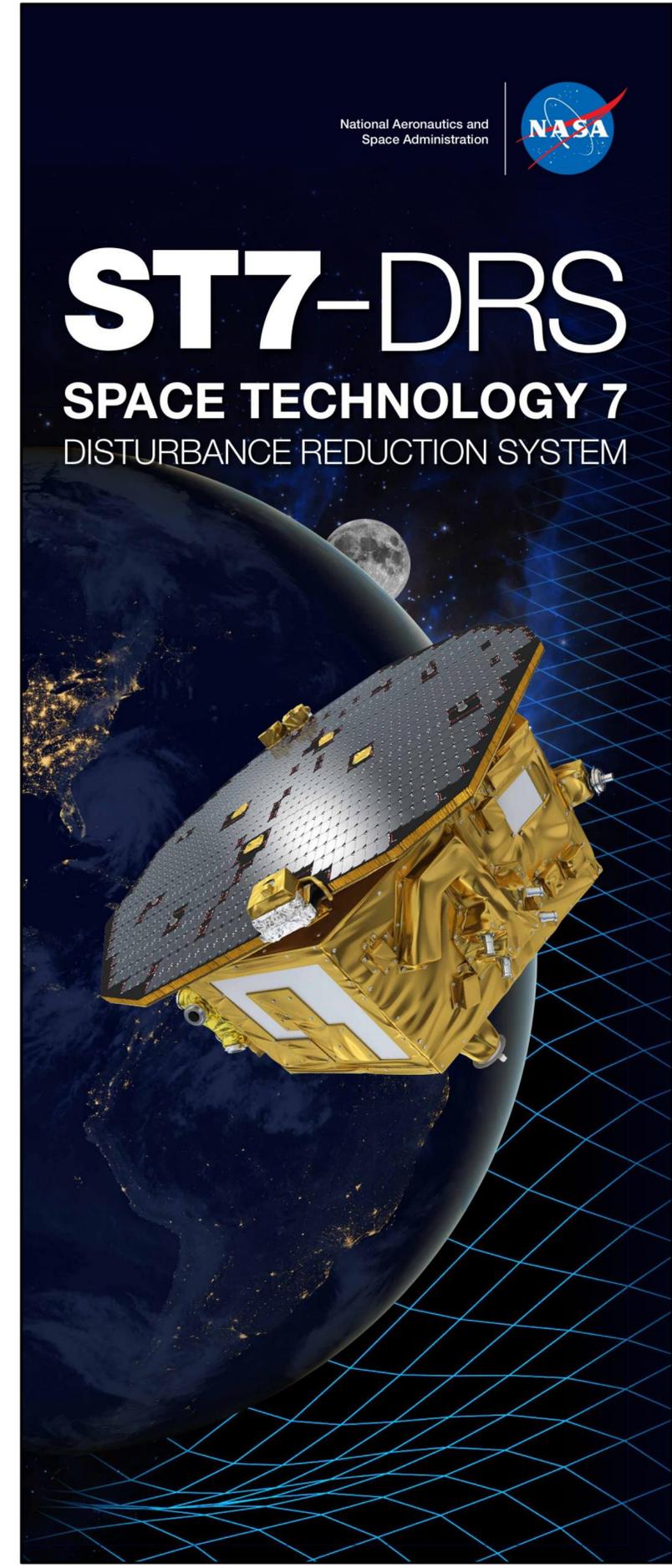
### DISTURBANCE REDUCTION SYSTEM

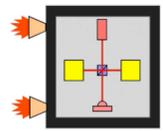
# ST7-DRS on LISA Pathfinder

Charles Dunn<sup>1</sup>, Phillip Barela<sup>1</sup>, Curt Cutler<sup>1</sup>, Richard Denzin<sup>1</sup>, Garth Franklin<sup>1</sup>, Jacob Gorelik<sup>1</sup>, Oscar Hsu<sup>2</sup>, Shahram Javidnia<sup>1</sup>, Irena Li<sup>1</sup>, Peiman Maghami<sup>2</sup>, Colleen Marrese-Reading<sup>1</sup>, Jitendra Mehta<sup>1</sup>, James O'Donnell<sup>2</sup>, Andrew Romero-Wolf<sup>1</sup>, Jacob Slutsky<sup>2</sup>, Ira Thorpe<sup>2</sup>, S. Harper Umfress<sup>1</sup>, John Ziemer<sup>1</sup>

on behalf of the LISA Pathfinder Team

1. Jet Propulsion Laboratory, California Institute of Technology
2. NASA Goddard Space Flight Center

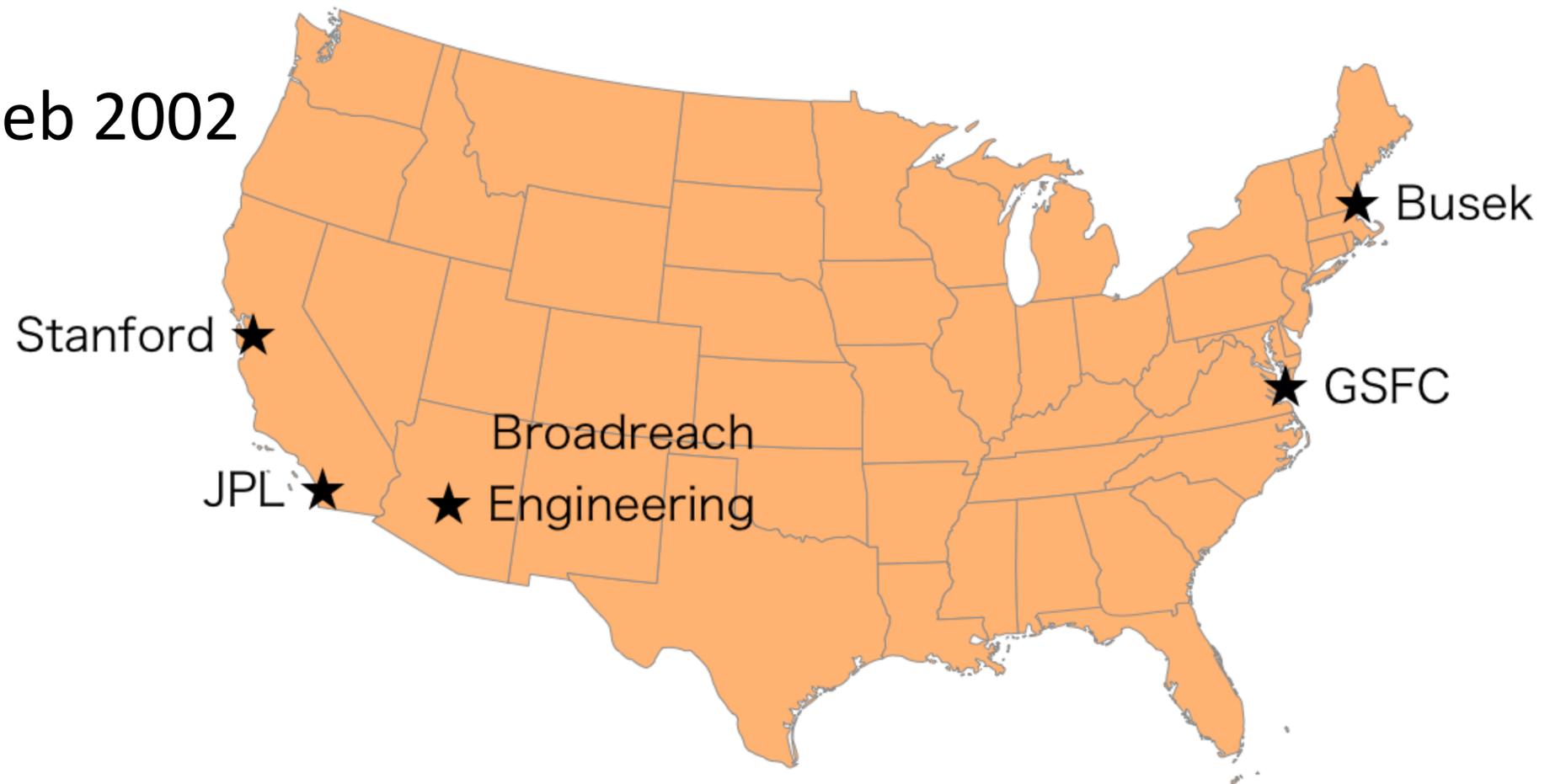


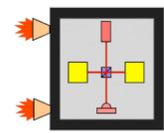


# What is ST7-DRS?



- ▶ DRS = Disturbance Reduction System
- ▶ ST7 = Seventh New Millennium Program Technology Demo
- ▶ ST7-DRS is a NASA contribution to an ESA mission (MOO)
  - ▶ Flight Demo of Drag Free Control
  - ▶ Selected for phase A July 2001
  - ▶ Selected for implementation Feb 2002





# ST-7 Team



## JPL

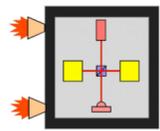
Aaron Fishman  
 Alan Littlefield  
 Alberto Ruiz  
 Allen Sirota  
 Andrew Romero-Wolf  
 Andy Carmain  
 Andy Kuhnert  
 Bill Folkner  
 Bob Krylo  
 Bob Spero  
 Bryan Bell  
 C-P Kuo  
 Cami Vongsouthy  
 Charlene Valerio  
 Charles Benson  
 Charley Dunn  
 Cheryl Asbury  
 Chris England  
 Colleen Marrese  
 Curt Cutler  
 Dave Nguyen  
 David Barne  
 David Carr  
 David Johnson  
 David Miller  
 David Robinson  
 David Robison  
 David Spencer  
 David Jackson  
 David J. Seidel  
 Denise A Hollert  
 Dennis Kern  
 Don Lewis  
 Don Nguyen  
 Donald Sevilla  
 Ed Konefat  
 Eduardo Dorantes  
 Frank Ramirez

Gani Ganapathi  
 Garth Franklin  
 Gary Plett  
 Glenn Anderson  
 Glenn Aveni  
 Guy Man  
 Henry Abakians  
 Hui-Yin Shaw  
 Ira Katz  
 Jacob Chapsky  
 Jacob Gorelik  
 Jeffrey Srinivasan  
 Jeffrey Tien  
 Jennifer Lafkas  
 Jennifer Marquez  
 Jim Smith  
 John Anderson  
 John Blandino  
 John Cardone  
 John Pensinger  
 John Tallon  
 John Wellman  
 John Ziemer  
 John (Jack) Stocky  
 Jordan Evans  
 Juan Fernandez  
 Kevin Tan  
 Kim Young Utit  
 Lawrence Azevedo  
 Lee Johnson  
 Lee Rogers  
 Long Chen  
 Lorraine Avila  
 Manuel Gamero  
 Mark Cooper  
 Mark Anderson  
 Mark Miller  
 Michael Cherng  
 Michael Connally  
 Michael Greene

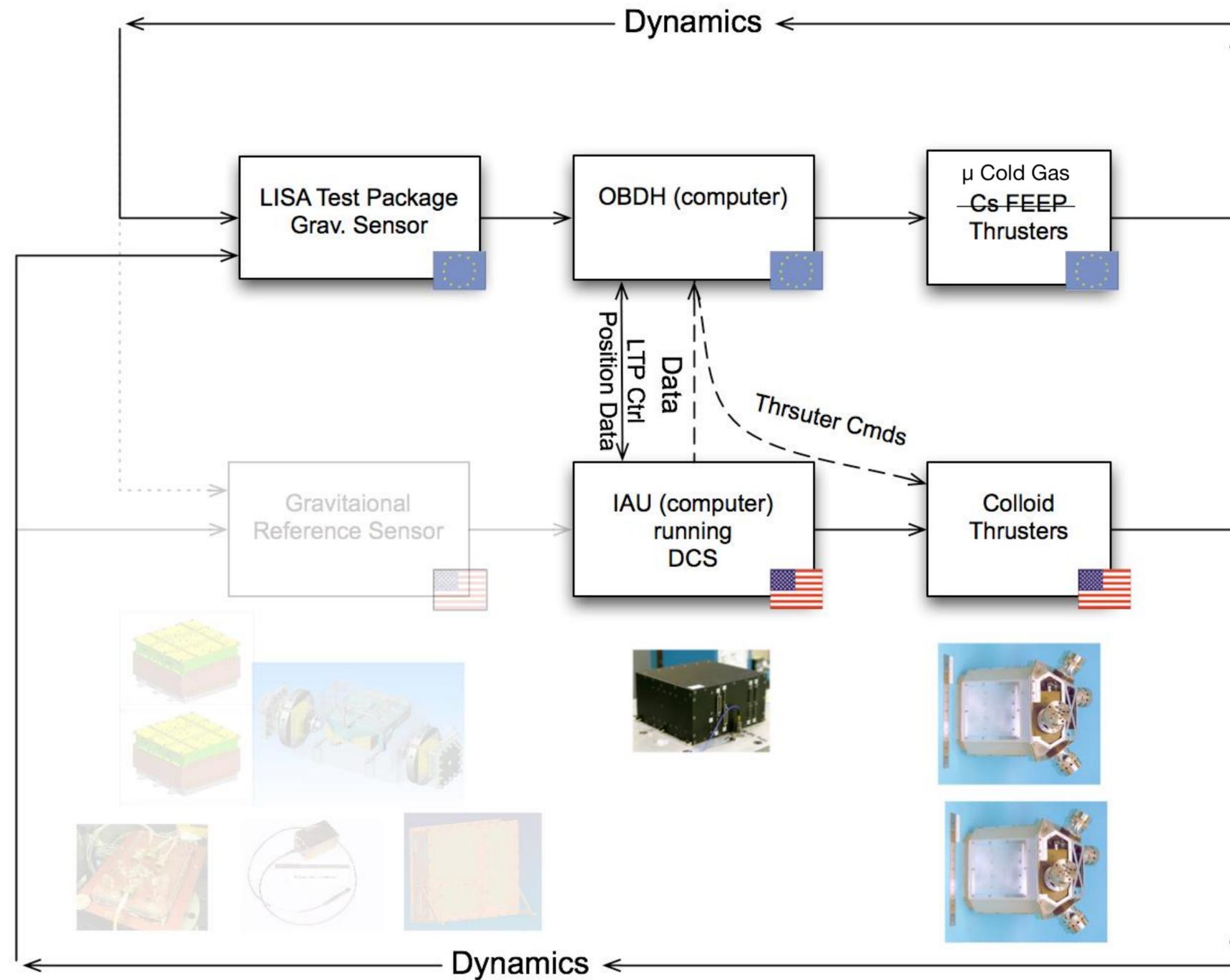
Michael Starkey  
 Mike Girard  
 Mike O'Connell  
 Mike Knopp  
 Otfrid Liepack  
 Paul Willis  
 Pawan Gogna  
 Philip Mayers  
 Phillip Barela  
 Rajendra Parikh  
 Rick Denzin  
 Rigo Gonzalez  
 Robert Kolasinski  
 Robert Valencia  
 Robin Bruno  
 Rosemary Diaz  
 Ryan Montgomery  
 Shawn Malik  
 Stephen Kulczycki  
 Steven Patrick  
 Stuart Clark  
 Susan Barry  
 Tom Otto  
 Tom Ramsey  
 Tom Randolph  
 Tony Hull  
 Werner Schwarz

## GSFC

Bob Rapp  
 Ira Thorpe  
 Jacob Slutsky  
 Jeff D'Agostino  
 Jim O'Donnell  
 Kathie Blackman  
 Landis Markley  
 Oscar Hsu  
 Peiman Maghami

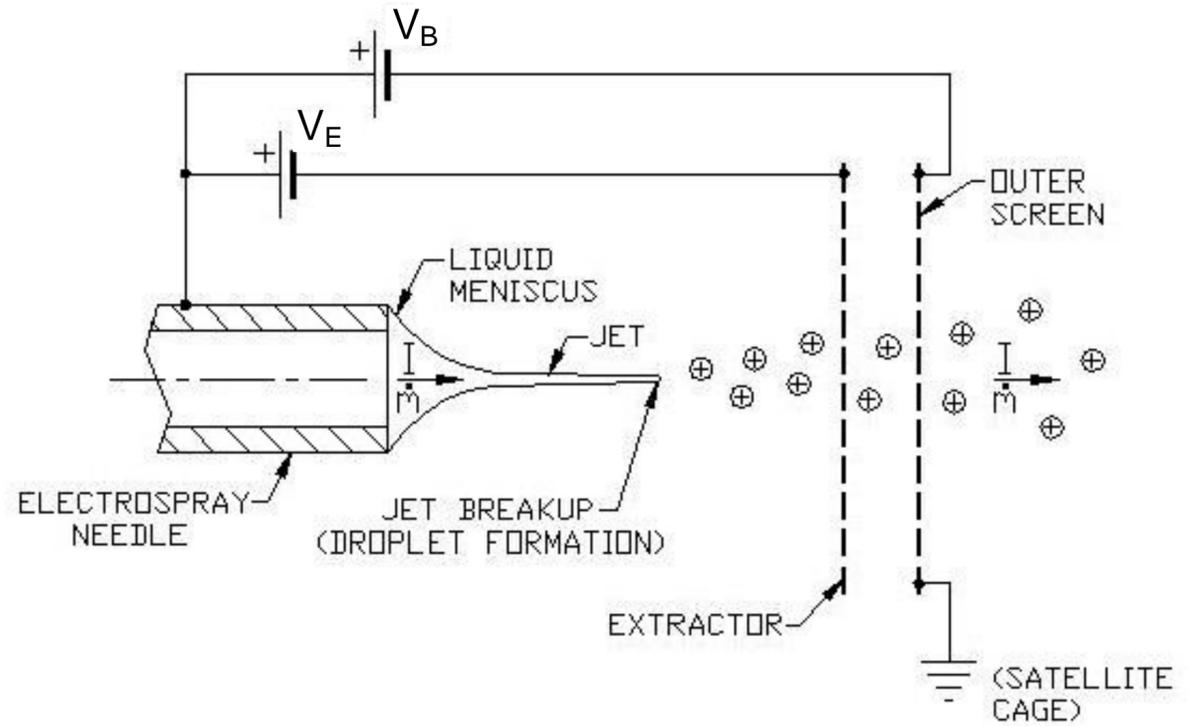
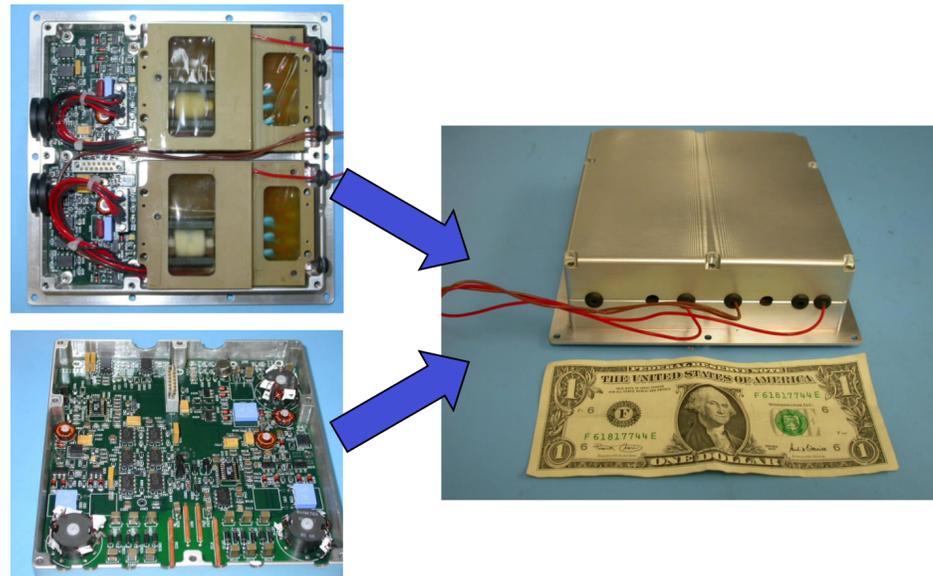
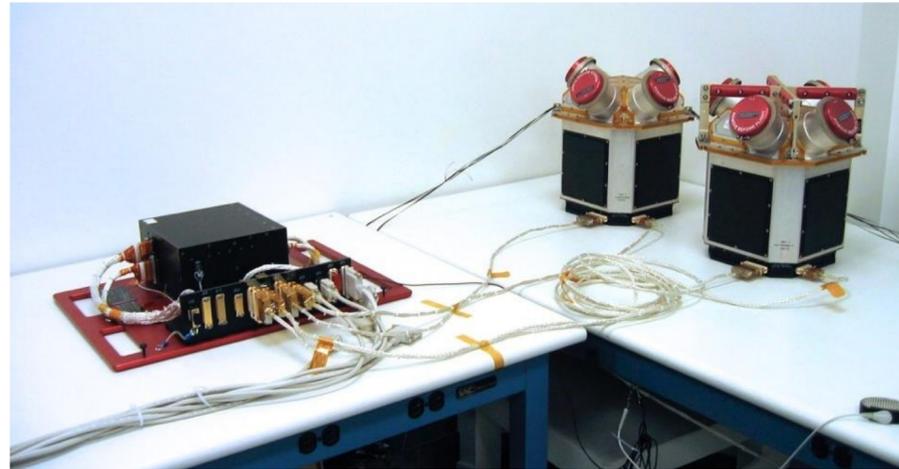


# System Description After Sept 12, 2005 Descope

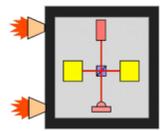




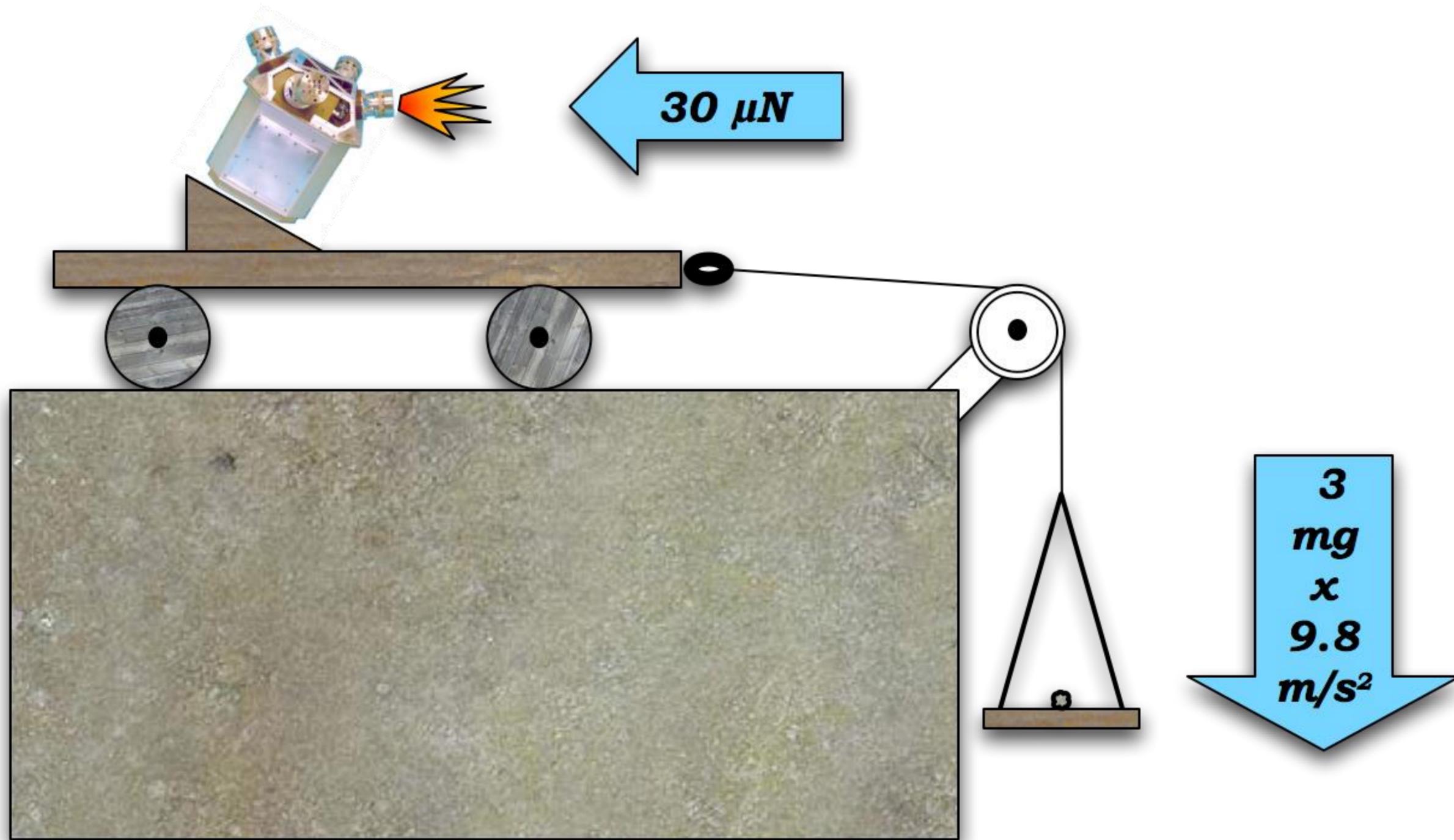
# Colloid Micro-Newton Thruster (CMNT)



- ▶ 5-30  $\mu\text{N}$  range
- ▶ 0.1  $\mu\text{N}$  control
- ▶ 0.1  $\mu\text{N}/\text{VHz}$  thrust noise

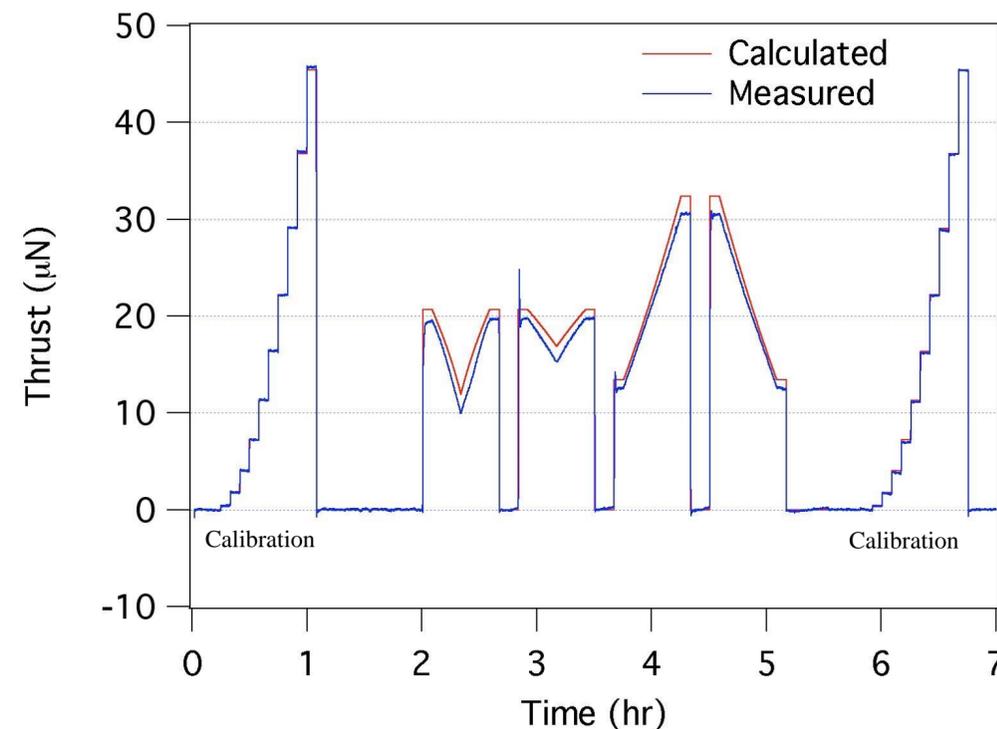
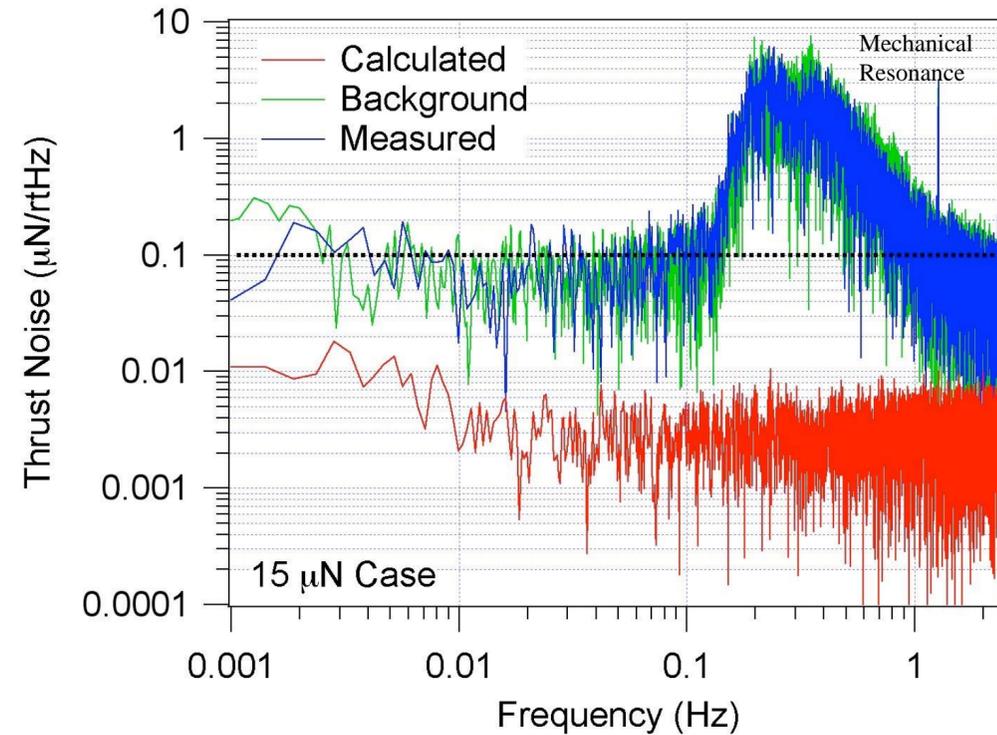


The maximum thrust produced by the colloid micronewton thrusters is equal to the weight of a 3 mg grain of sand!





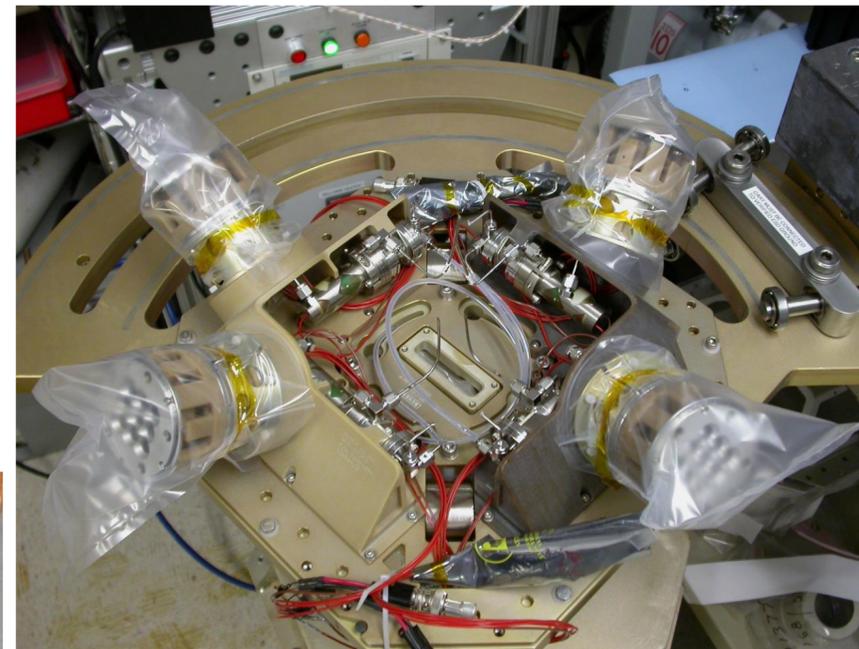
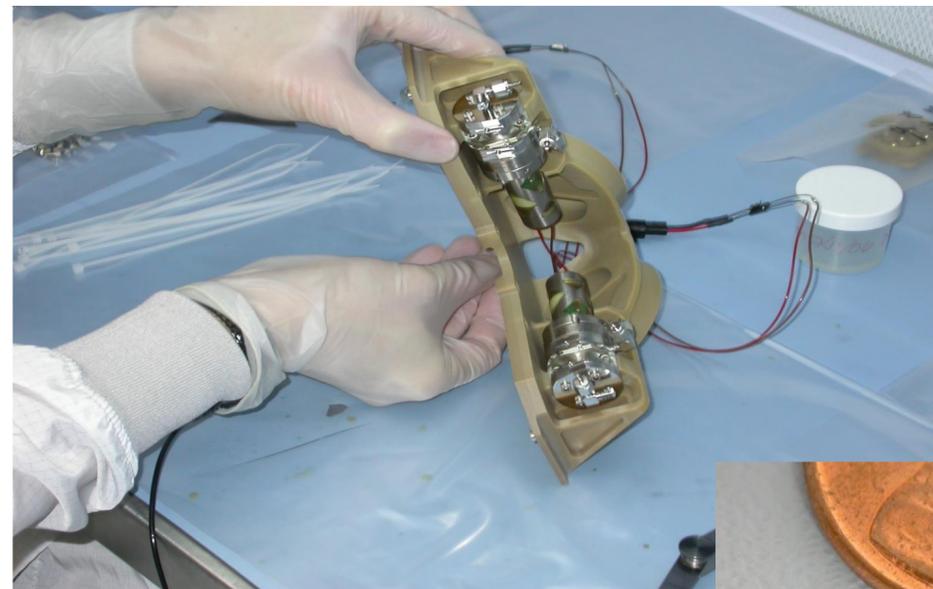
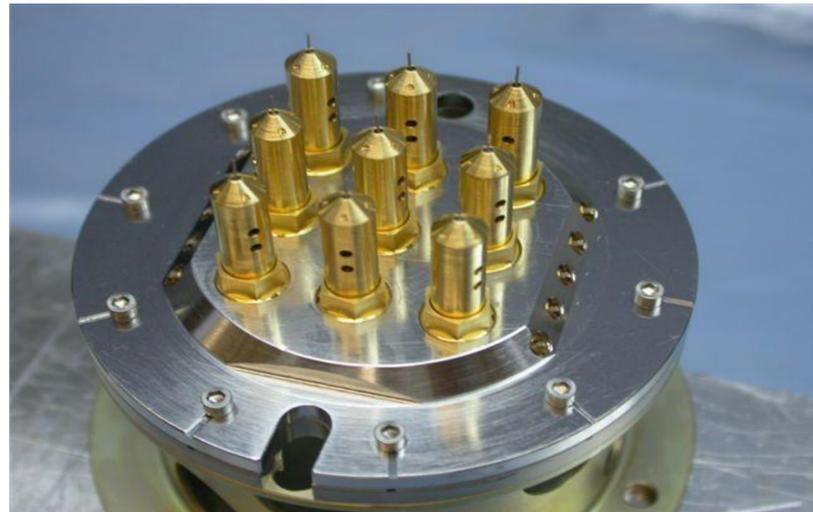
# Thrust Stand Measurements



- Busek's magnetically levitated thrust stand has the best resolution and background noise characteristics *in the world*
  - $<0.1 \mu\text{N}$  resolution,  $\sim 0.1 \mu\text{N}/\text{Hz}$  equivalent background noise from 0.005 to 0.1 Hz
  - Older JPL and Busek torsional pendulum microthrust stands have 2x lower resolution
  - ESA has been trying to develop a similar diagnostic tool without much success to date
- Colloid thruster resolution and thrust noise now verified by direct measurement
  - Previous estimations all done by calculation based on beam voltage and current measurements with 100% thrust efficiency
  - Measured thrust is 92-96% lower than a perfectly efficient thruster and closely follows expected  $T \propto V^{0.5} I^{1.5}$  relation
  - Measured thrust noise is not above background levels, which meet ST7 requirements from 0.005 to 0.05 Hz
  - Calculated thrust noise is an *order of magnitude below requirement*



# Flight Assembly





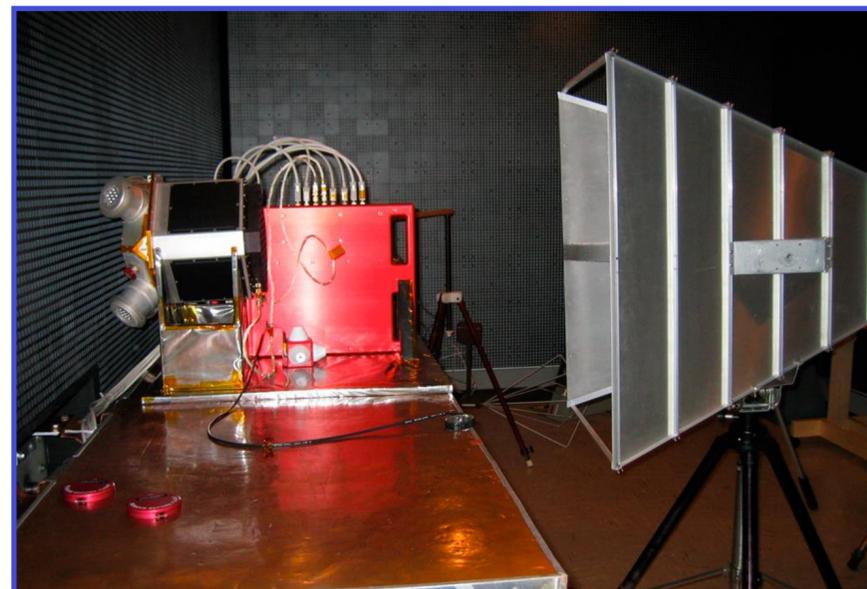
# Clusters - Post-Delivery [to JPL] 2008



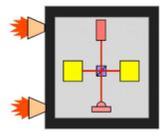
**February 24th/May 18th: Clusters 1 & 2 [respectively]  
Arrives at JPL**



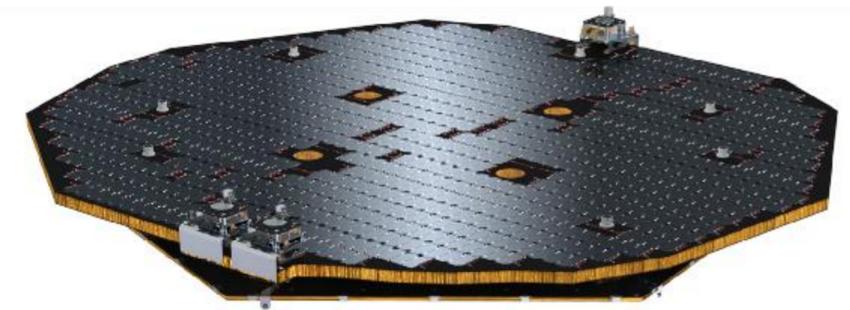
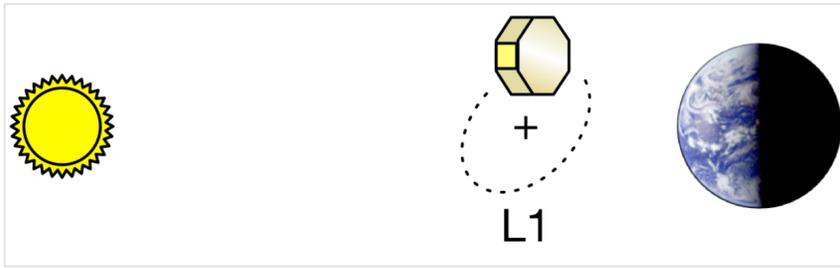
**March 11th/May 28th: Magnetics Testing Completed  
(Clusters 1 & 2 [respectively] )**



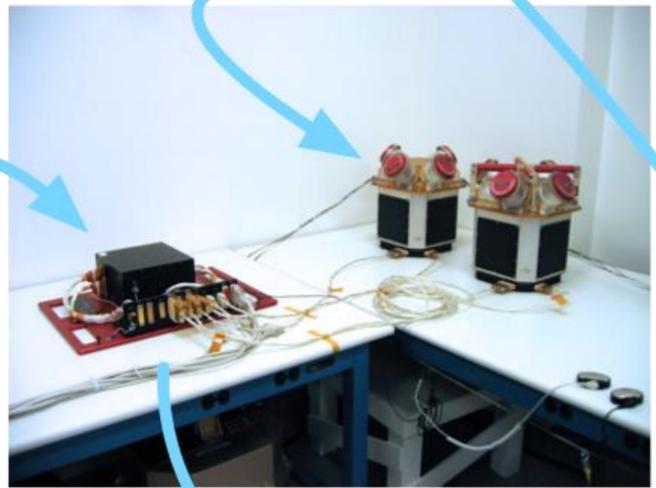
**March 18th: EMC Testing Complete on Cluster 1**



# LISA Pathfinder Mission & DRS

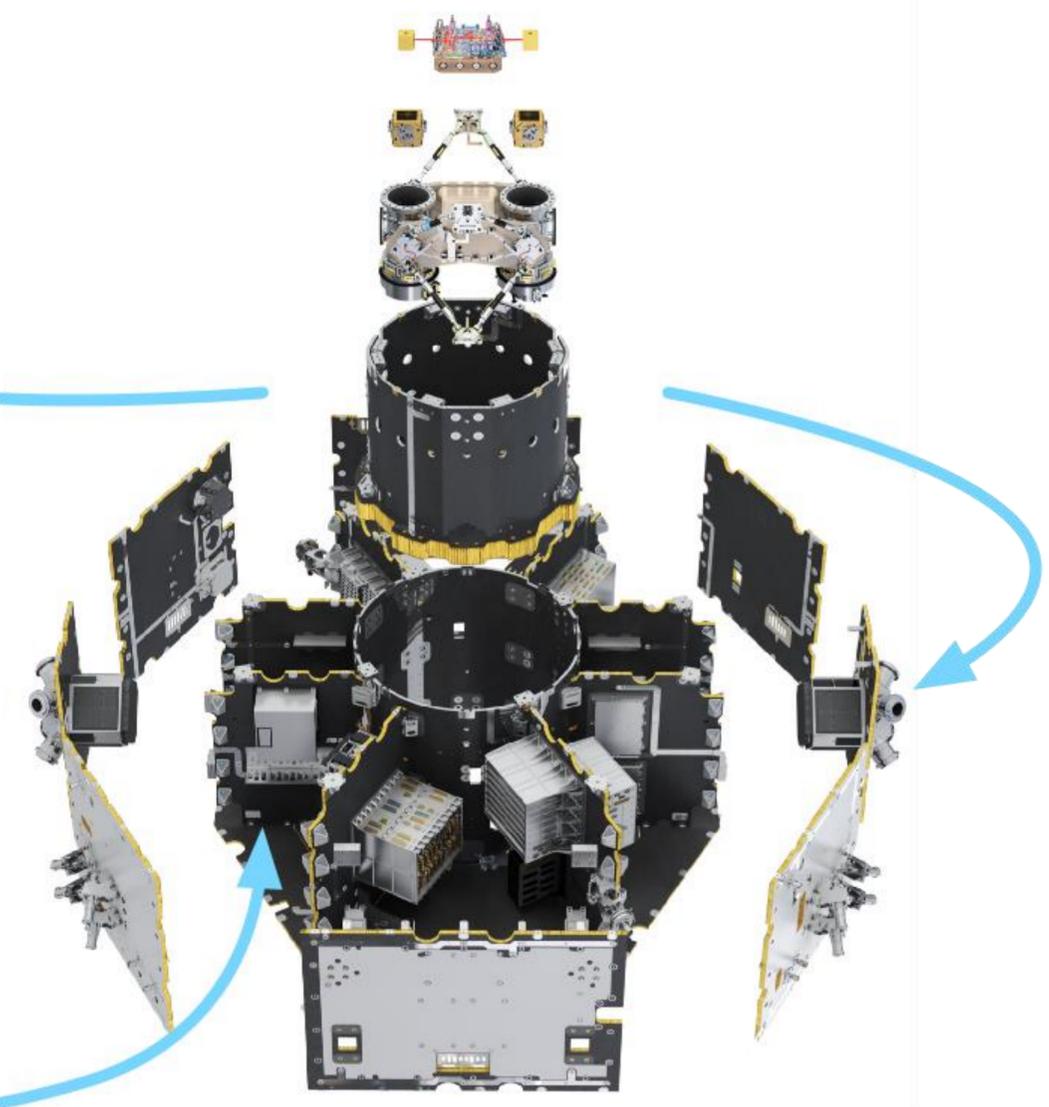


**Colloid Micro-Newton Thrusters**  
2 cluster of 4 thrusters, each  
Busek Corp.

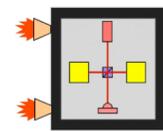


**Integrated Avionics Unit**  
Rad750, power switching & comm  
Broad Reach

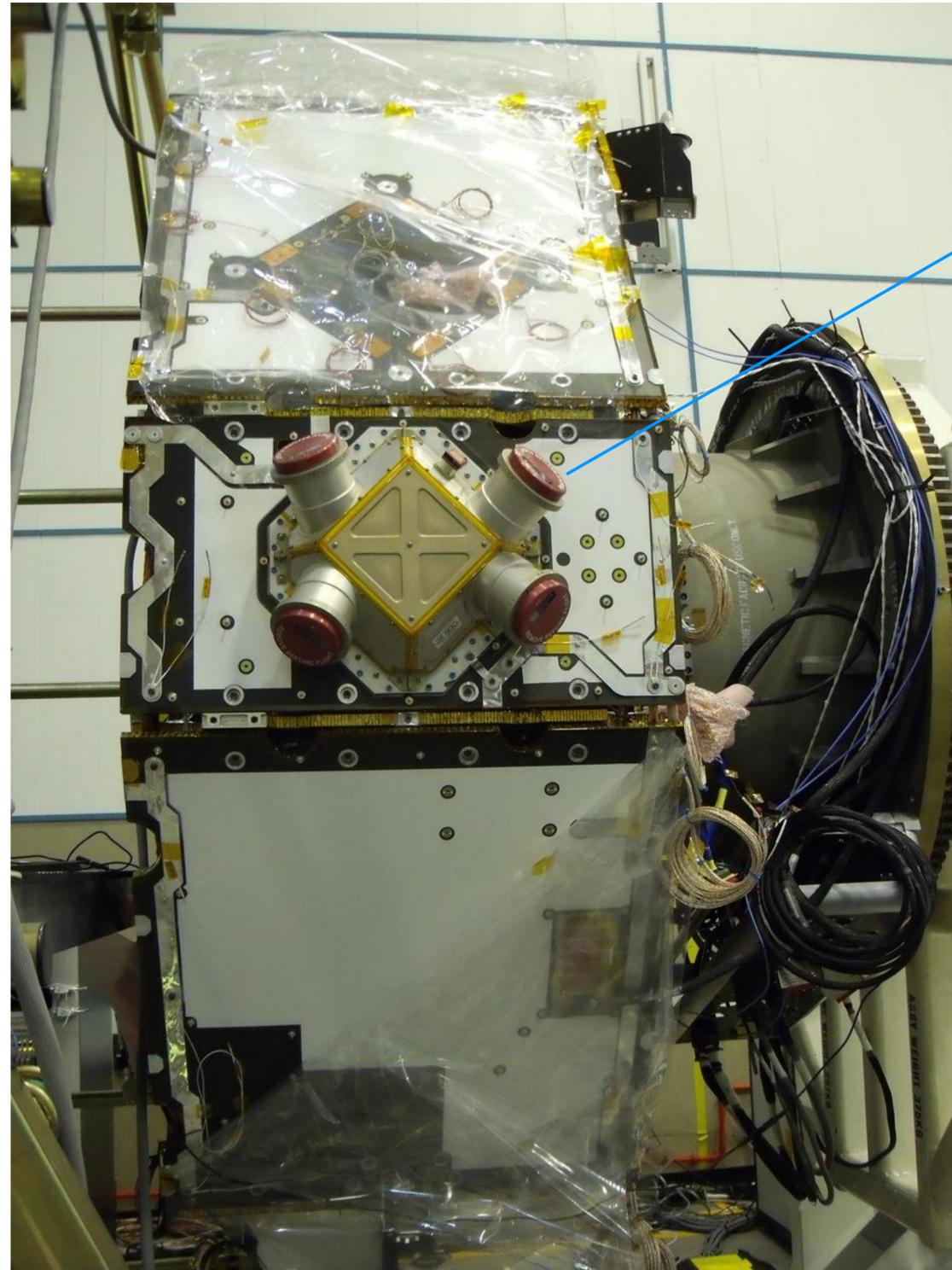
**Dynamic Control System Software**  
18 Degree of Freedom control  
Goddard Space Flight Center



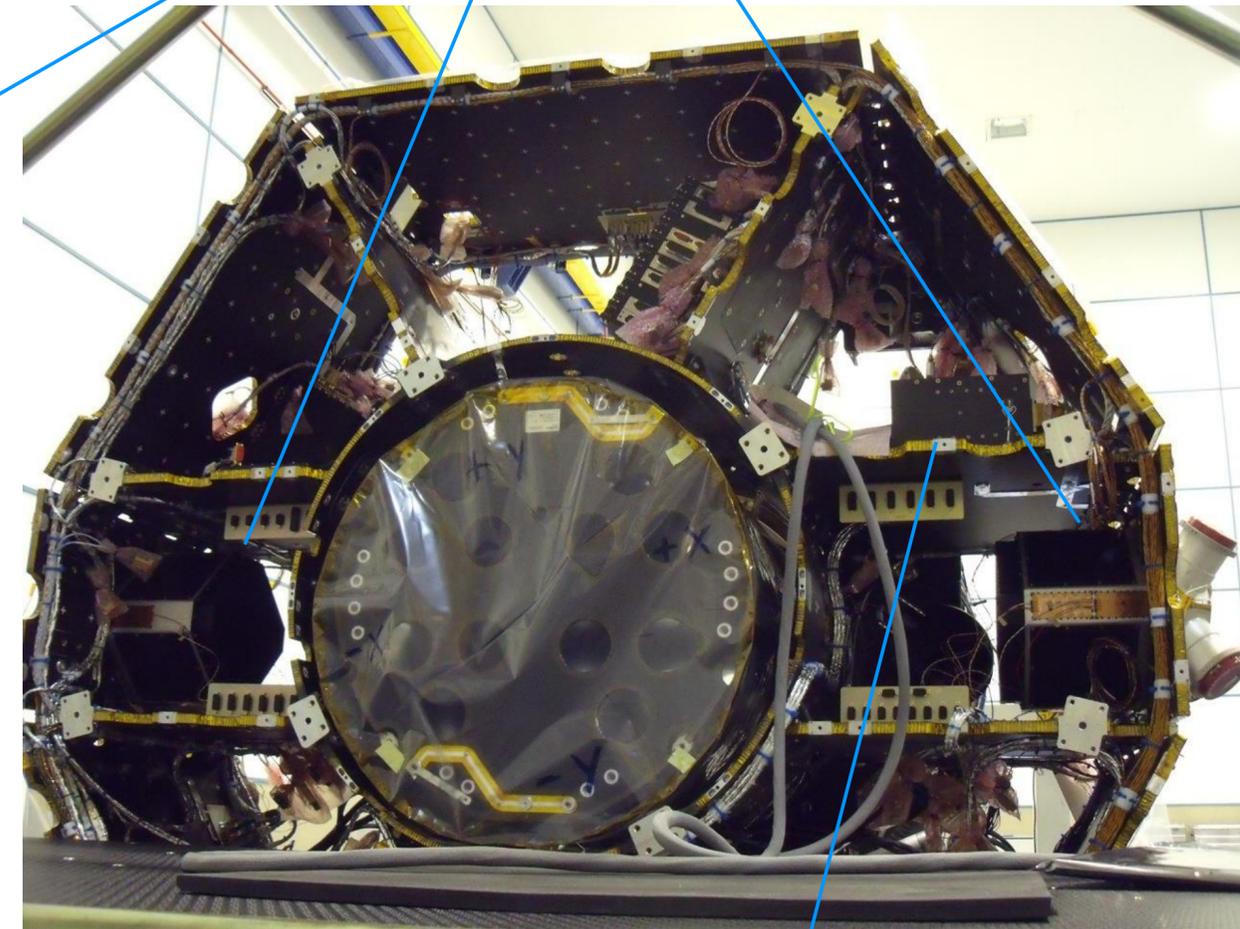
*exploded view © ESA*



# DRS Installed on LPF Spacecraft, Nov 2009

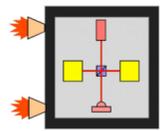


8 May 2013

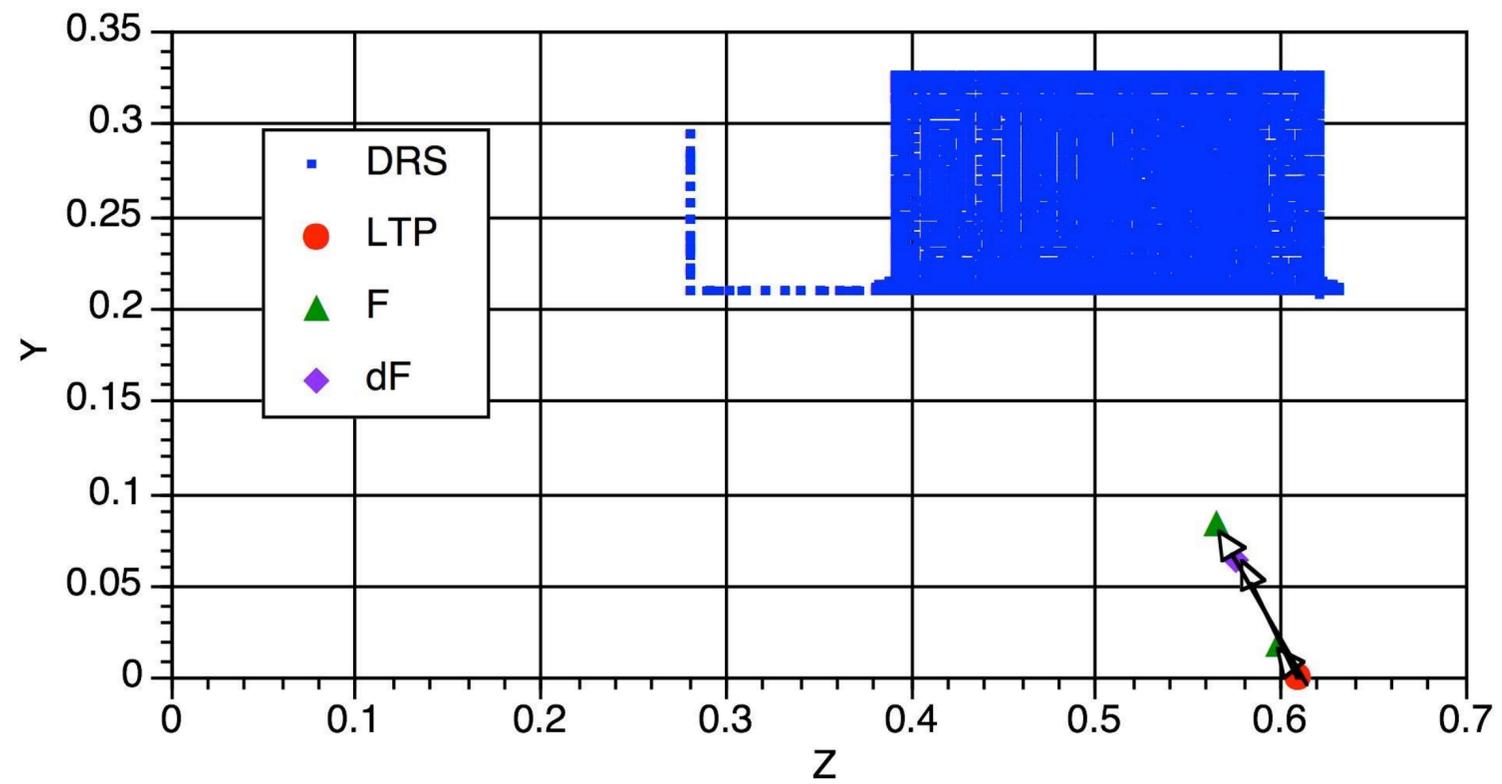
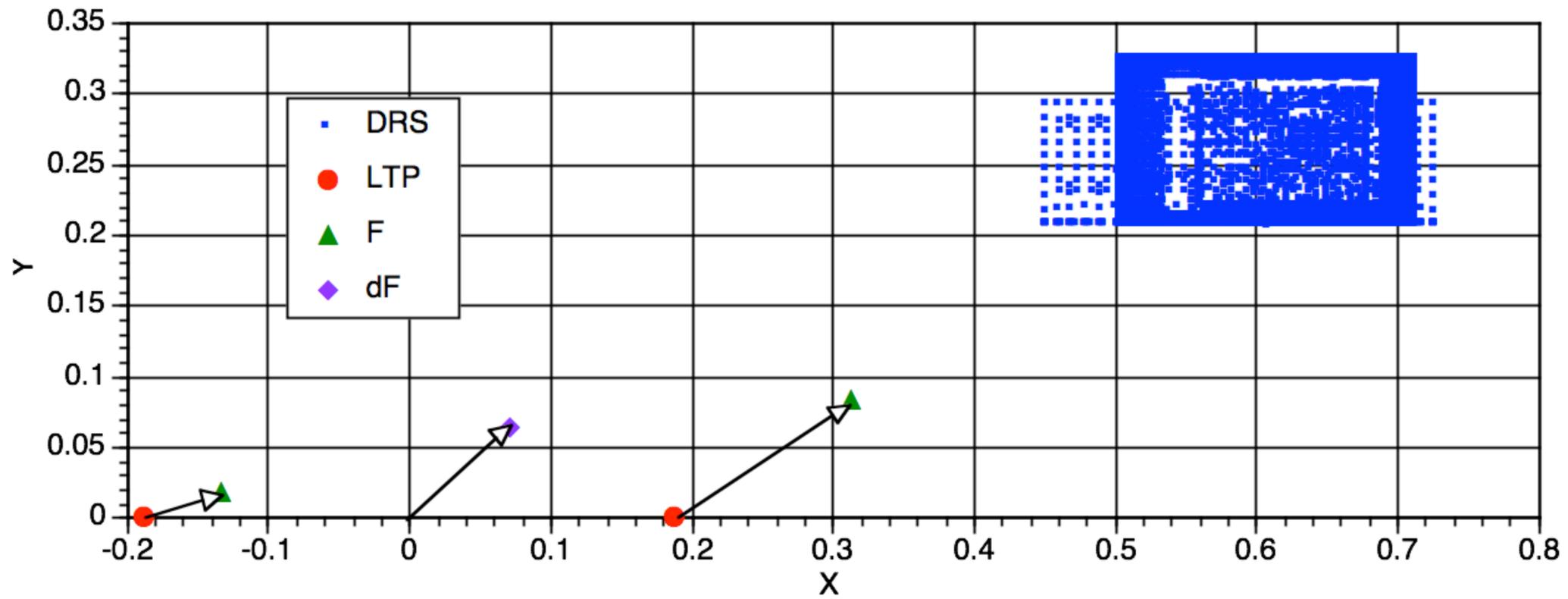


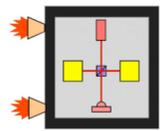
DRS Thruster  
Clusters (2)

DRS Integrated  
Avionics Unit

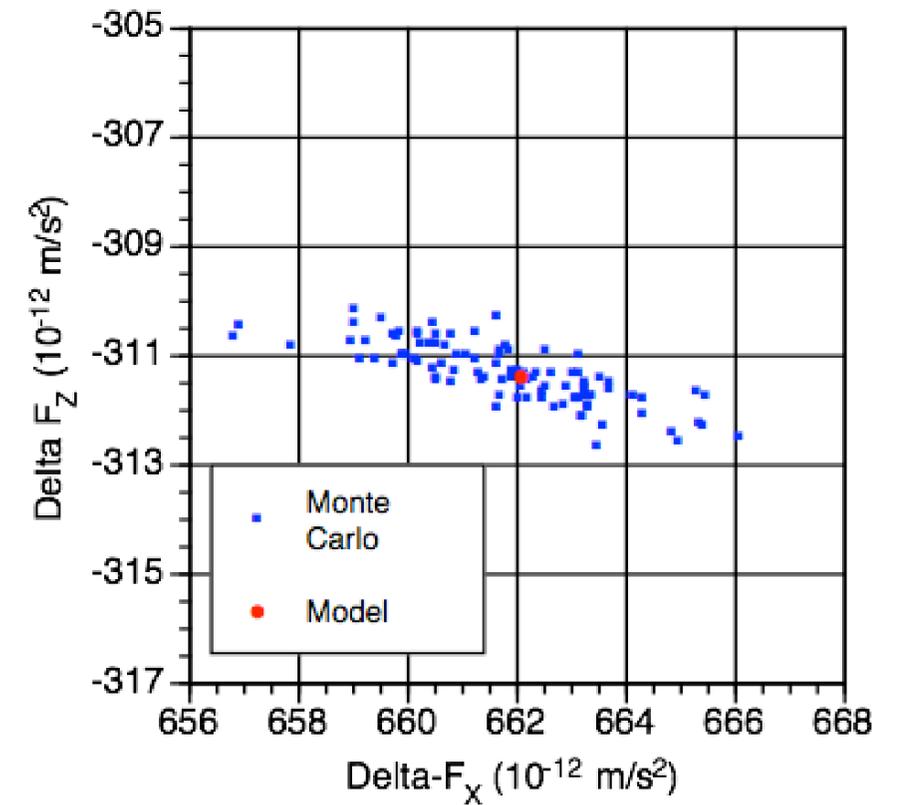
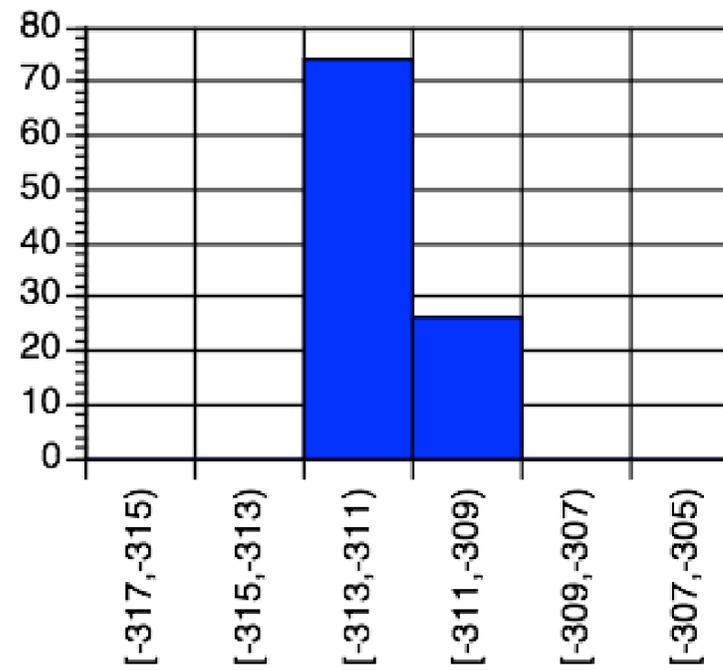
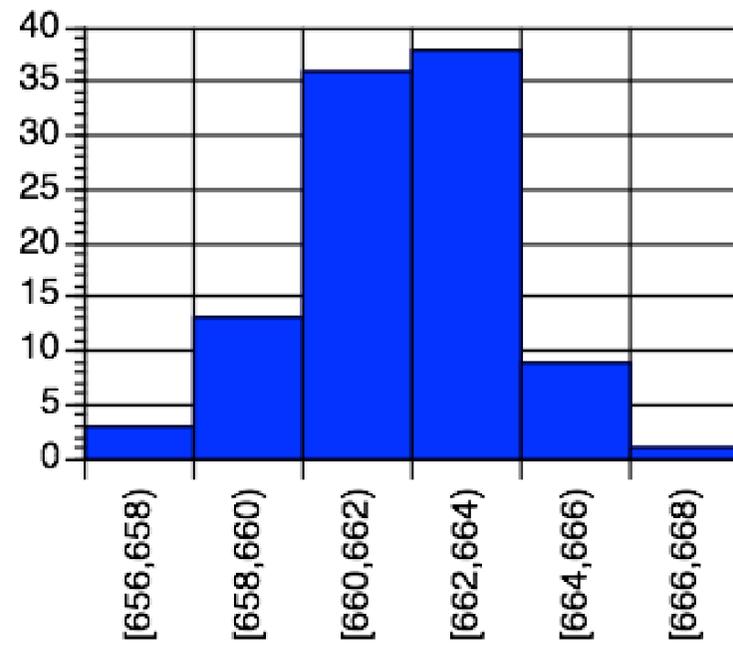
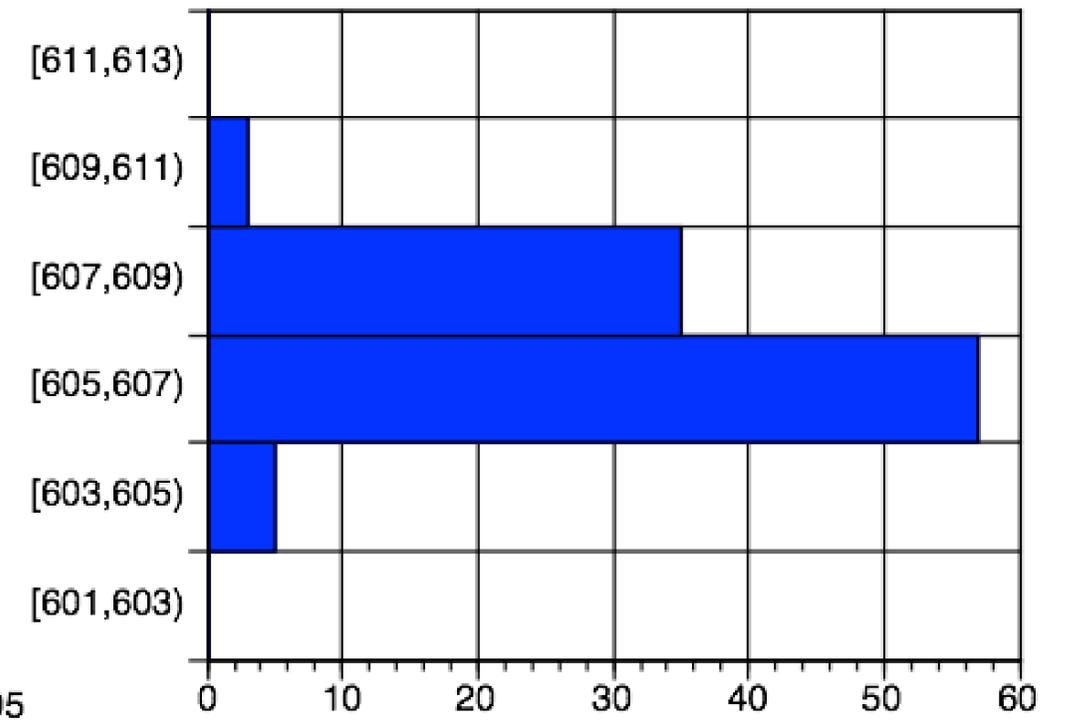
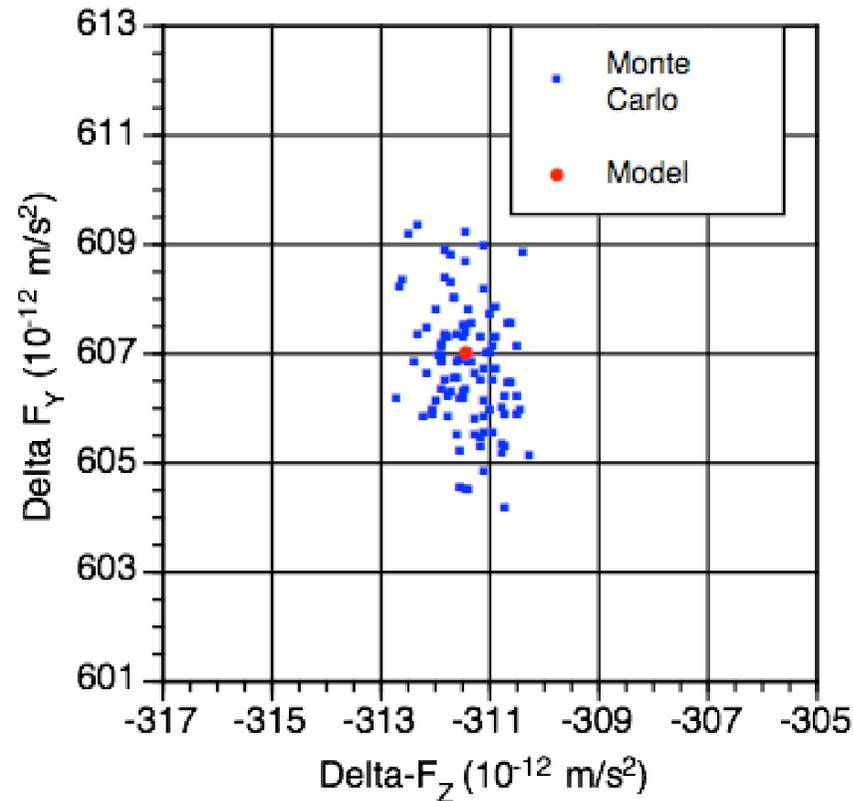
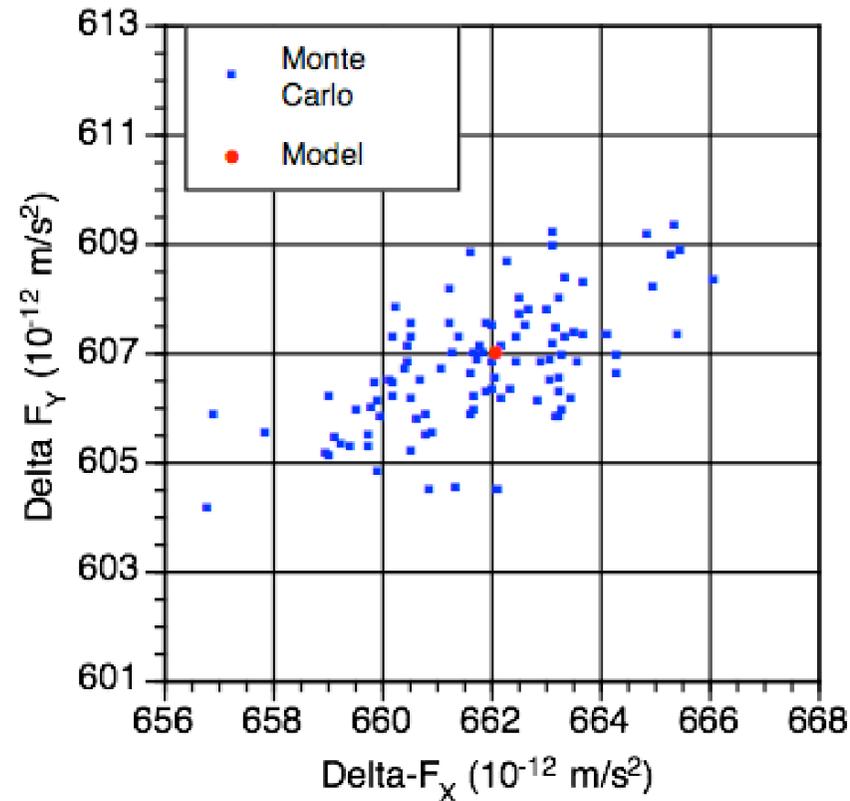


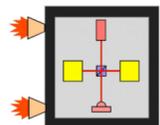
# Gravitational Field





# Monte Carlo Results





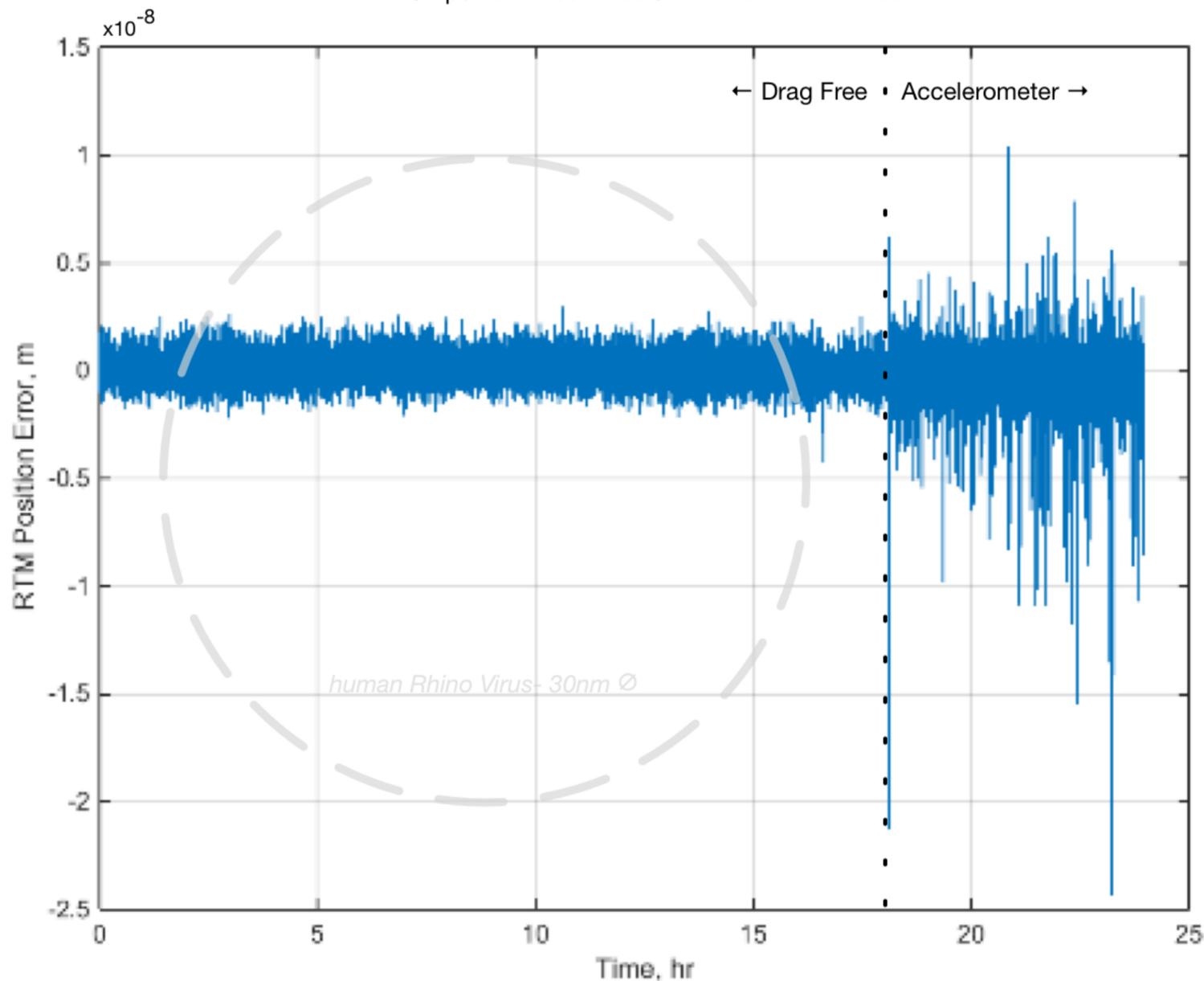
# Position Control



## Reference Test Mass X-Coordinate relative to S/C

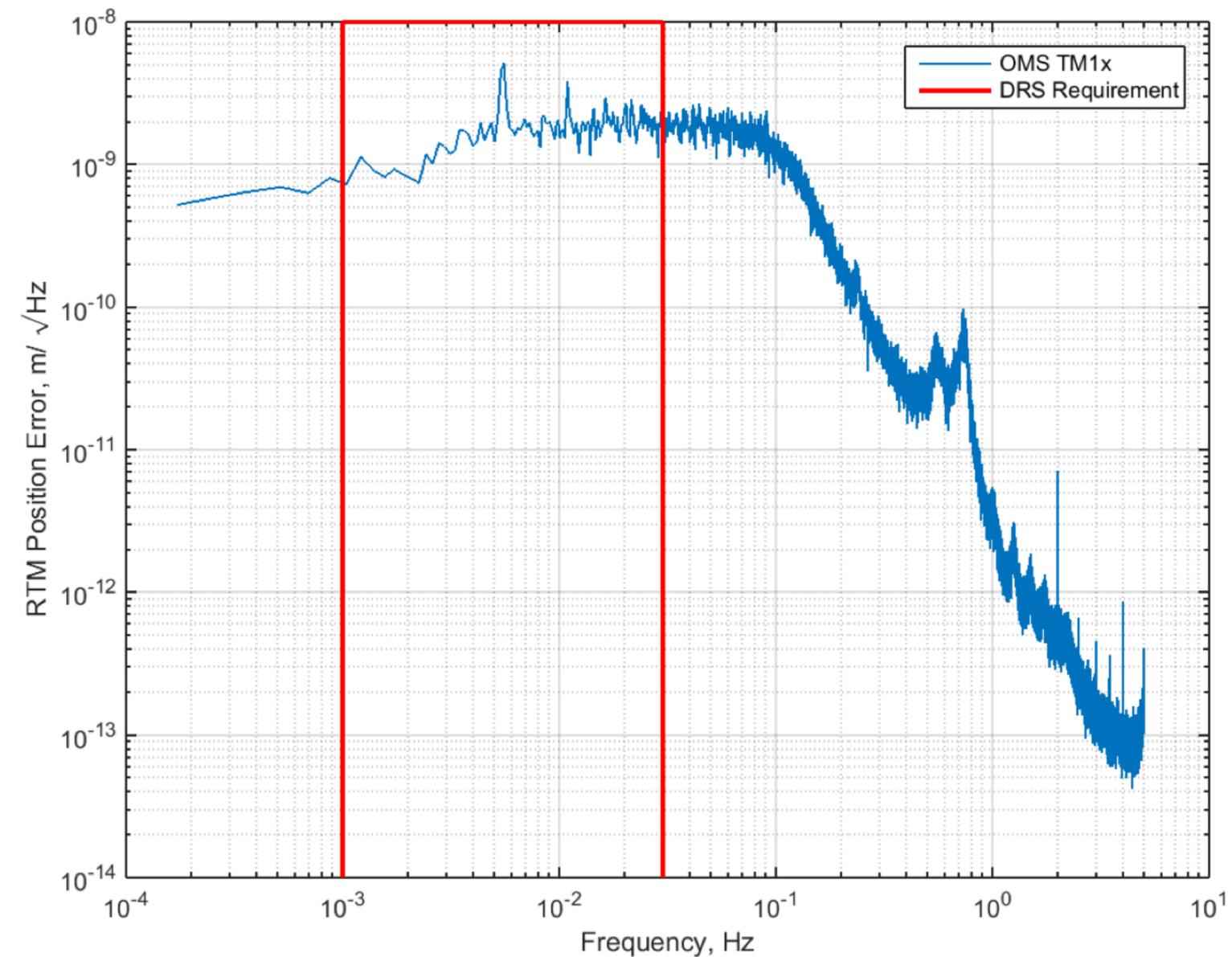
### Position Time History

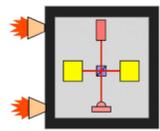
DRS ops 2016.235.11.53@2016.236.11.54 PF.dat



### Amplitude Spectral Density

DRS ops 2016.235.11.53@2016.236.11.54 PF.dat

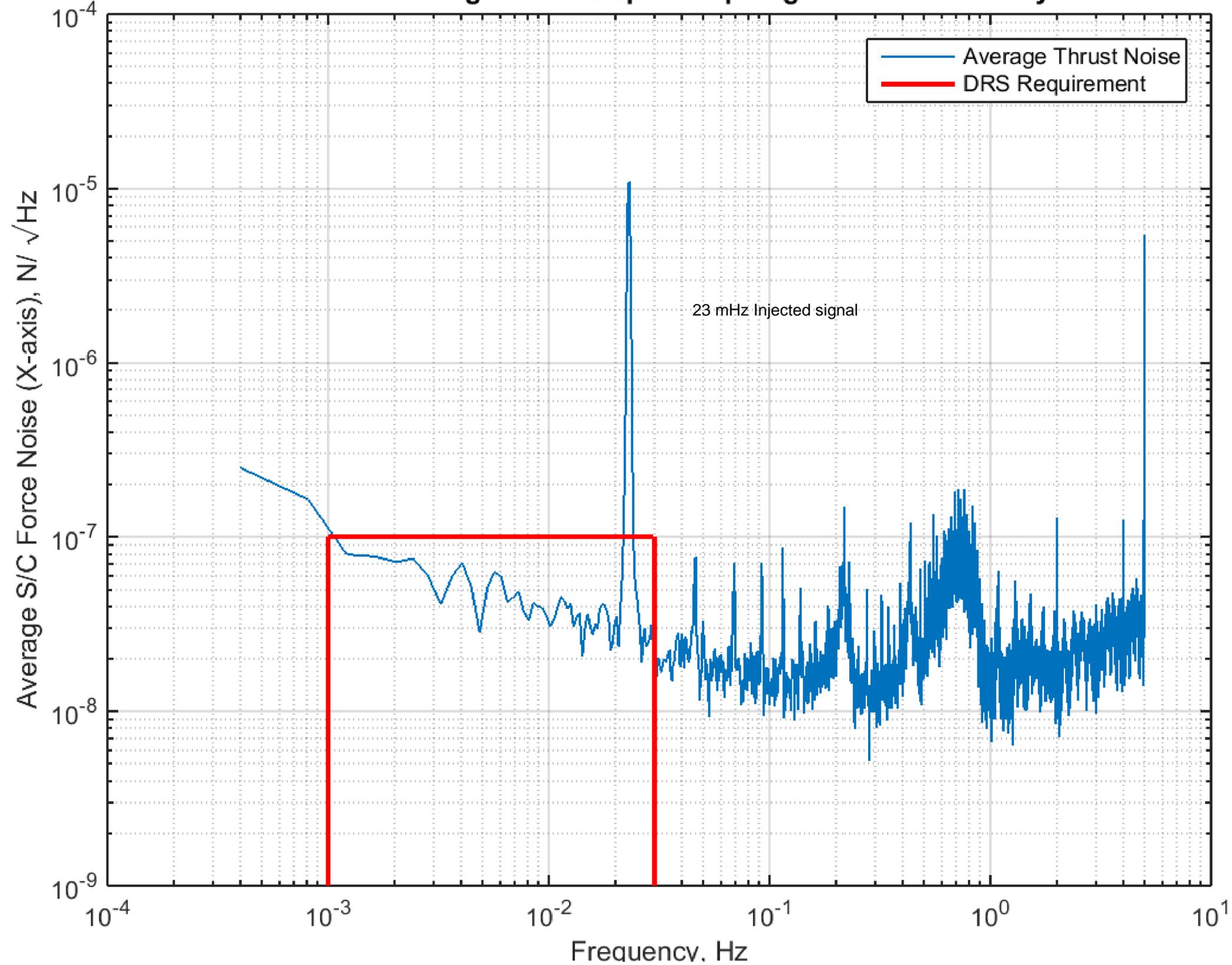


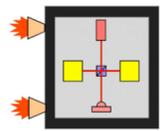


# Propulsion Noise



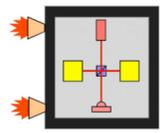
Based on the average of the 8 open-loop Segments of T3 on Day 245





# Major Conclusions

- ▶ ST7 was a successful demonstration of drag-free control at a performance level necessary for a LISA-type GW observatory
- ▶ The space disturbance environment is understood at the  $0.1 \mu\text{N}/\sqrt{\text{Hz}}$  level
- ▶ The Colloid Micro-Newton Thrusters performed at a noise level predicted by pre-launch testing
- ▶ The European LTP Inertial Sensor functioned in the DRS system as expected
- ▶ 18 degree of freedom drag-free control operated reliably
- ▶ The self-gravity model of DRS is correct at the few  $\text{pm}/\text{s}^2$  level



# Current Status



- ▶ On October 27, Thruster 4 was rendered inoperable due to an unrecoverable short
- ▶ A hybrid drag-free mode was developed using a constant thrust produced by four spacecraft cold gas thrusters and the remaining colloid thrusters → Slightly degraded performance
- ▶ ST7 is approved for extended operations:
  - Characterize and understand cause of Th-4 short
  - Improvements in thruster control loop
  - Higher resolution thrust
  - Improved thruster characterization enabled by SW update
- ▶ Expected mid-March to mid-April 2017